Magneto-optic Kerr effect study of a two-step reorientation transition of an ultrathin magnetic film

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The magnetic reorientation transition for ultrathin Fe films on Gd is studied. At low temperatures, the films are magnetized in plane and at intermediate temperatures they undergo a reorientation to out of plane. The reorientation is attributed to the reducing magnetization of Gd as it approaches its Curie temperature and the perpendicular magnetic anisotropy at the Fe surface. Detailed measurements of the reorientation were made *in situ* using the magneto-optic Kerr effect (MOKE). The first step, at low temperature, is a continuous, reversible reorientation of the surface moment from in plane to canted out of plane; a corresponding peak in the susceptibility identifies it as a second-order phase transition. The second step is a discontinuous, irreversible rotation from this canted direction to perpendicular to the film plane; thermal hysteresis of the magnetization identifies it as a first-order phase transition. The MOKE thermal hysteresis loop shows that the Gd surface region participates in the first-order phase transition. [S0021-8979(00)31508-0]

Recent studies of reorientation transitions (RT) in ultrathin magnetic films have addressed the classification of these phenomena as either continuous or discontinuous.[1,2] In the RTs of ultrathin films, the competition between magnetic anisotropies drives the magnetization direction through 90°, from perpendicular to in plane (or vice versa), as a function of temperature or thickness. A RT is classified as either continuous or discontinuous, depending on whether the magnetization flows thorough all intermediate angles between the initial and final directions.[3] Previous work[1] showed that the RT of this system, from in plane at low temperature to perpendicular above the Gd Curie temperature (T_C^{Gd}) is accomplished in two steps: a continuous transition from in-plane to canted magnetization at low temperature and a discontinuous transition from canted to perpendicular at higher temperature. New data presented here corroborate that conclusion. In addition, we show that the Gd surface region participates in the discontinuous part of the transition.

Film growth, structural and chemical characterization, and magnetic measurements were made in an ultrahigh vacuum system and the results were previously reported.[4] In brief, the Y(0001) single-crystal substrate was cleaned by ion sputtering and films of Gd were deposited to a thickness of 15 nm at a substrate temperature of 473 K. A subsequent anneal of 700 K for 1 min produced a highly ordered, clean and magnetically soft film. Iron was then deposited at room temperature. Both films were grown by electron beam evaporation. The low energy electron diffraction pattern and Auger spectra showed substantial interfacial mixing and disorder, indicating that the Fe/Gd forms an amorphous interface alloy. Magnetic measurements were performed *in situ* with the magneto-optic Kerr effect (MOKE) in remanent and ac susceptibility modes.[5]

The remanent magnetization of a 1.5 monolayer (ML) Fe film on Gd is shown in Fig. 1 using longitudinal (in-plane) and polar (out-of-plane) MOKE. It shows a nominally in-plane magnetization below T_C^{Gd} and a strictly out-of-plane remanent magnetization, M_r, above T_C^{Gd}. Closer inspection shows that M_r develops an out-of-plane component well below T_C^{Gd}. No hysteresis was observed in these curves. At high temperature, M_r goes to zero near 360 K.

Figure 2 shows the real part of the polar MOKE susceptibility (in phase with the applied field), χ', for a second 1.5 ML Fe/Gd film, obtained with the applied field perpendicular to the plane. On the scale of Fig. 2, the corresponding χ' for a *bare* Gd film is essentially zero unless the applied field is in plane, where a peak forms at $T_C^{\mathrm{Gd}} \approx 293\,\mathrm{K}$. The addition of an ultrathin Fe layer produces three peaks, identifying three important temperatures. A large peak at 375 K forms near the ordering temperature of the Fe overlayer.[6] The region of

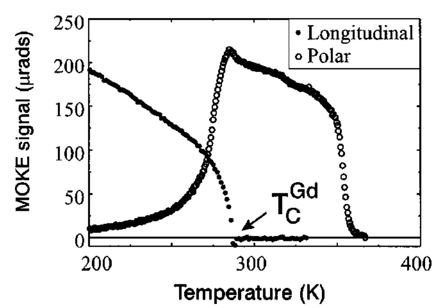

FIG. 1. Longitudinal (for in-plane) and polar (out-of plane) remanent MOKE vs temperature for a 1.5 ML Fe/Gd film.

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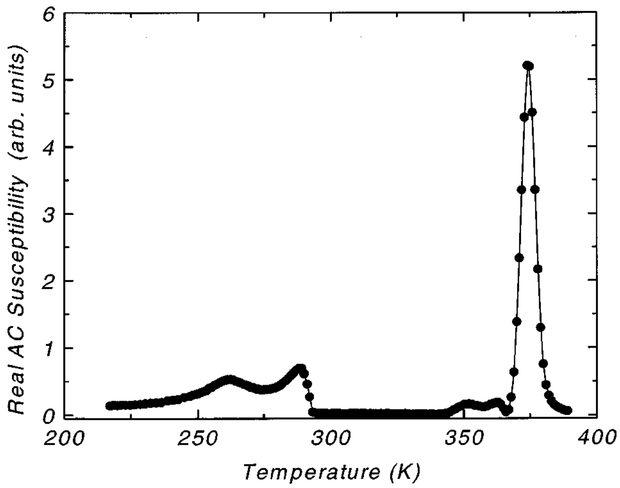

FIG. 2. Real part of the ac magnetic susceptibility in polar MOKE for a second 1.5 ML Fe/Gd film.

interest for the RT is for $T \leq T_C^{\mathrm{Gd}}$, where two peaks are observed. One of these forms appears at T_C^{Gd} and the other appears at 260 K.

The region of interest in Fig. 2 is examined in detail in Fig. 3. Near the peak in χ' at 260 K, the imaginary part of the susceptibility (i.e., out of phase with the field), χ'', rises from zero as the M_r first develops an out-of-plane component.[7] For the data of Fig. 1, which show a small out-of-plane component even at 200 K, the lowest temperature peak was at 150 K. While the two higher temperature peaks are always associated with the Fe and Gd ordering temperatures, the position of the low temperature peak is sensitive to the annealing conditions of the Gd film. Higher temperature anneals reduced the temperature of this peak and the coercivity, suggesting a dependence on the magnetocrystalline anisotropy of the Gd. The coincidence of out-of-plane remanence, as determined by χ'', and a peak in χ', is consistent with the onset of a continuous RT and a second-order phase transition.[8] This is corroborated by the thermal reversibility of this peak.[1] We conclude that the first step of the RT is a second-order phase transition from in plane to canted.

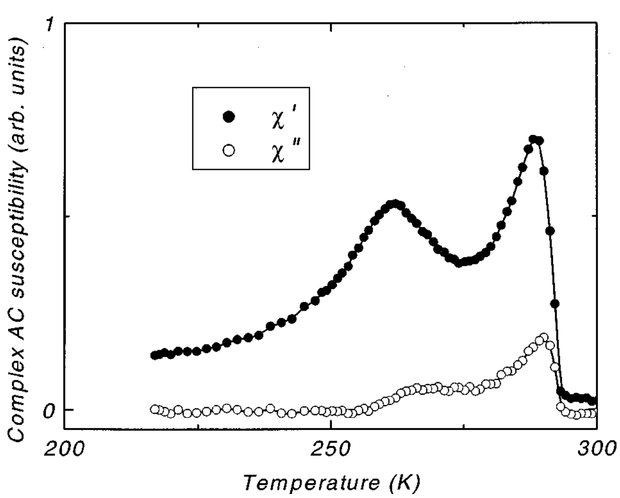

FIG. 3. Complex ac susceptibility in polar MOKE in the temperature region of the reorientation transition for the data of Fig. 3.

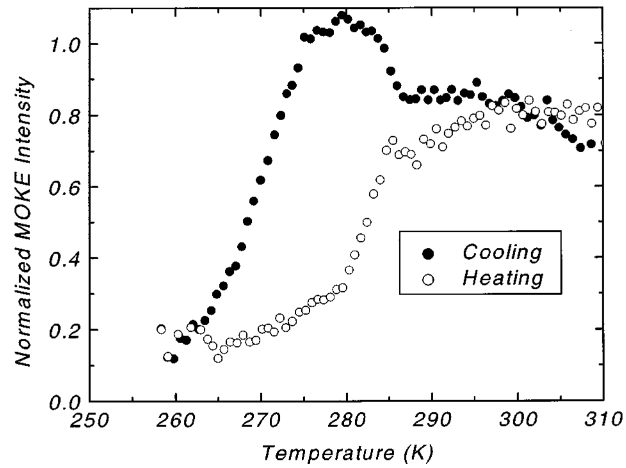

FIG. 4. Thermal hysteresis loop in polar MOKE of 1.5 ML Fe on Gd in zero applied magnetic field for a third 1.5 ML Fe/Gd film.

In order to investigate the magnetic response of the system near T_C^{Gd}, M_r was measured for a third film with *zero applied magnetic field*, in cooling and in heating. The MOKE data are shown in Fig. 4. For these measurements, the film was magnetized out of plane with a single field pulse at 300–310 K, cooled in zero field to a temperature below that for which hysteresis was observed, typically to 250–260 K, and then reheated in zero field to the starting temperature. Thermal hysteresis shows that the second step of the RT is a first-order phase transition. These MOKE measurements agree with previously published spin-polarized electron measurements.[1]

One significant difference between the MOKE and spin-polarized electron data is the anomalous rise of the signal on cooling below 285 K. This rise was not seen in the spin-polarized electron data.[1] Because of its greater penetration depth, the MOKE shows both the Fe surface and Gd film response, as opposed to the spin-polarized electrons, which are only surface sensitive. Since the MOKE and spin-polarized electron thermal hysteresis loops have different shapes, we conclude that the Gd surface participates in the discontinuous part of the RT. An interpretation of the rise in the MOKE signal during cooling is the formation of a domain wall at the Gd surface. In this proposed model, the domain wall position between the perpendicularly magne-

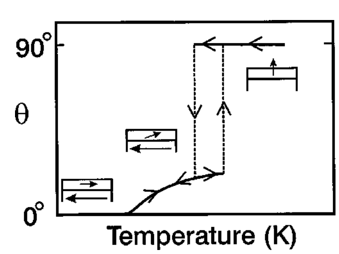

FIG. 5. Schematic of the magnetization angle vs temperature for 1.5 ML Fe on Gd.

tized Fe surface and in-plane Gd film is metastable. In cooling, the domain wall initially nucleates relatively deep into the Gd film where it remains in a metastable equilibrium to low temperatures. In heating, the domain wall forms closer to the surface because it has warmed from an in-plane (or canted) state.

In conclusion, the RT of ultrathin Fe on Gd is accomplished in two steps as illustrated in Fig. 5. The first is a continuous reorientation of the magnetization from in plane at low temperature, to a canted direction. The second step is an irreversible, and presumably discontinuous, rotation from this canted direction to perpendicular to the film plane. This data, in combination with previously published spin-polarized electron data, show that the Gd surface region participates the discontinuous step of the RT. This supports a model of domain-wall formation and pinning at the Gd surface near its Curie temperature.

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